NUMERICAL STUDY OF STORAGE CAPACITY AND POTENTIAL GROUND UPLIFT DUE TO CO_2 INJECTION INTO KUTAI BASIN BY USING COUPLING HYDROMECHANICAL SIMULATOR

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Abstract: Carbon capture and geological storage (CCGS) is one of the most feasible options in mitigating global warming. CCGS can be applied in capturing CO_2 emission produced by large stationary sources, transporting to a site and then injecting it into a deep sedimentary basin. Kutai Basin in East Kalimantan is potential basin for CO_2 geological storage. However, this requires a detail and comprehensive information about storage capacity of the basin, and it senvironmental impact associated with CO_2 leakage to groundwater and geomechanical deformation due to the injection of CO_2 into the basin. This paper presents numerical study of the injection of CO_2 into Kutai Basin and potential geomechanical deformation as a consequence of the change of stress and hydraulic pressure due to the injection. Numerical simulations were undertaken by modeling 3-dimensional Kutai Basin with a injection well at 800 meters. The injection was specified at 3024 ton/day within one year period. To simulate the process of CO_2 migration in the basin including its geomechanical efffect, a coupling hydromechanical simulator of TOUGH2-FLAC3D was utilized. It was found that CO_2 injection is able to increase hydraulic pressure in rock formation of the basin as CO_2 plume migrates, escaping the injection point. As a result, the hydraulic pressure rises from its natural pressure 9 MPa to 13 MPa and the total volume of CO_2 injected becomes 1.1 million tons. The injection also generates a ground uplift, accounted for about 304 mm. The results suggested that the basin has large storage capacity for CO_2, however its severe ground uplift needs to be carefully examined prior to commercial CO_2 injection in a field scale.

Keywords: CO_2 sequestration, Kutai Basin Kalimantan, Hydromechanical Simulator, Ground Uplift, Storage Capacity.

Introduction

Multi approaches are urgently needed to mitigate severe impact of global warming. They include the development of efficient and alternative energy such as wind energy, solar power, biomass, and the development of carbon capture and geological storage (CCS). The latter is recently considered as the promising option since this can enable the exploitation of the proven reserves of fossil fuels but still in low amount of CO_2 emission (Benson, 2004). CCS is a process of separating CO_2 emission produced by large stationery sources such as industrial plants and power stations, compressing the emission to a supercritical phase and then transporting it via pipelines to a suitable geological formations, such as deep sedimentary basins (IPCC, 2005). Indonesia has at least six sedimentary basins which are considered as potential for CO_2 geological storage. They are North West Java Basin, East Java Basin, Kutai Basin, North Sumatra Basin, Central Sumatra Basin, and Southern Sumatra Basin. Iskandar et al. (2013) has examined the suitability and storage capacity of those basins for CO_2 geological storage. They used Bachu's Criteria (2003) and found that Kutai Basin is the most suitable basin due to the geological data are widely characterised and the tectonic condition is relative stable. The storage capacity of the basin was estimated 38 - 152 million tons CO_2 (Indonesia CCS Working Group, 2009). However, this numbers are rough estimation and they still need sufficient hydrogeological investigation. Besides that, environmental impact of CO_2 geological storage in Kutai Basin is needed to be examined. As Mathieson et al. (2011) found in In salah Algeria, large-scale CO_2 injection would be able to generate significant ground deformation. This paper aims to investigate CO_2 storage capacity of the Kutai Basin, including its potential geomechanical effect. Therefore, CO2 injections into idealized Kutai Basin were simulated. The simulation employed a coupled TOUGH2-FLAC3D, simulating multiphase flow of supercritical CO2 and saline water, coupled with heat transfer and rock deformation.

Kutai Basin

Kutai Basin is located beneath East Kalimantan (Figure 1), at the eastern edge of the Sunda Plate, resulted from the extension of southern Eurasia. The tectonic structure spreads NE-SW formed by Samarinda Anticlonirum (Moss et al., 1997). The stratigraphy of the basin can be described from young to old as Kampung Baru Bed, Balikpapan Bed, Pulau Balang Bed, Pamaluan Bed, Tuju Bed, Telakai Bed, dan Kuaro Bed (Table 1). Kampung Baru Bed consists of white sandstone with a sequence interbedded siltstone, mudstone and and lignite. Kampung Baru Bed is about 666 m thick, overlying Balikpapan Bed which consists on limestone with a interbedded sandstone and lignite, foraminifera and molusca. The Balikpapan Bed is 233 to 3500 m thick. CO_2 geological storage is supposed to be in the Balikpapan Bed due to its thickness is adequate to prevent the injected CO_2 flowing back to the groundwater or even to the surface. Therefore, the study simulated CO_2 injection point located at 800 meters below the surface. The injection well depth was selected following the similar depth of the Sleipner North Sea CO_2 injection project in Norway and more realistic for current CO_2 injection technology.

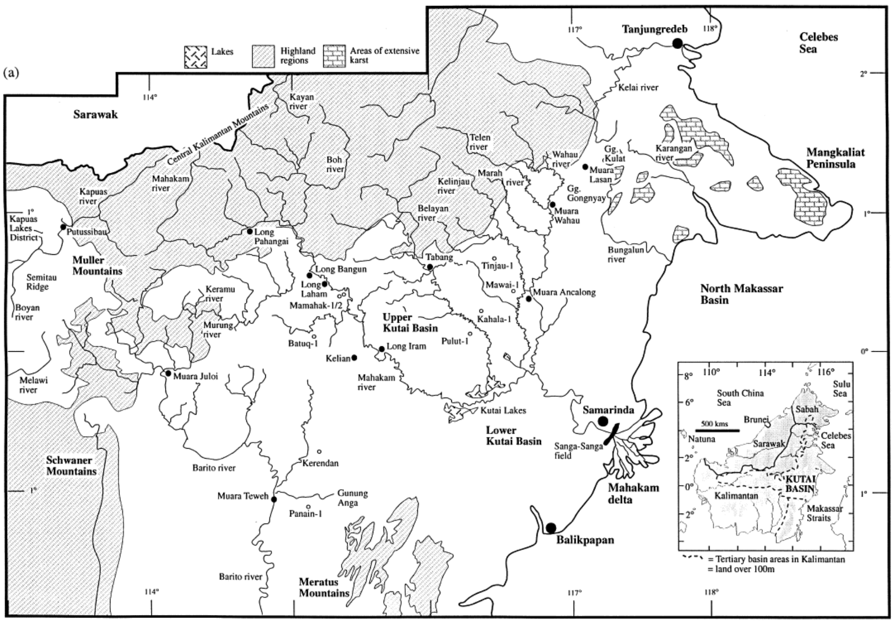

Figure 1. Kutai Basin (Moss et al., 1997)

Computational Model

Numerical study was performed by employing a geohydrological analysis of multiphase phase flow and thermal transport simulation of TOUGH2 (Pruess et al., 1999), coupled with a rock and soil mechanics computation of FLAC3D (Itasca, 2005). The ECO2N of TOUGH2 is a reservoir simulator developed specially for CO_2-brine mixtures in a realistic fluid property. The simulator can take real density and viscosity effect of CO_2 into account, including CO_2 solubility in liquid phase (Pruess et al. 2001). On the other hand, FLAC3D is a three-dimensional explicit finite-difference program for engineering mechanics computation. In FLAC3D, the explicit, lagrangian, calculation scheme and the mixed discretization zoning technique (Marti and Cundall, 1982) can be used to model the deformation of soil or rock at plastic flow when their yield limit are reached. Such external functions were used to transform the grid zones values in TOUGH2 to the grid point values in FLAC3D.

Table 1. Stratigraphy of Kutai Basin (Moss et al., 1997)

AGE		COLUMN	UNIT		LITHOLOGY	FAUNAL ZONES	THICKNESS (MT)
TERTIARY	MIOCENE-PLIOCENE		KAMPUNG BARU		SANDSTONE LIGNITE SILTSTONE MUDSTONE		0 TO 666
			BALIKPAPAN BEDS		LIGNITE WHITE SANDSTONE LIMESTONE		233 TO 3500
	EARLY MIOCENE		PULAU BALANG BEDS	UPPER	MUDSTONE THIN SANDSTONE COAL	*Globigerinoides sicanus* *Globigerinoides diminutus*	1265 TO 3000
				LOWER	GRAY SANDSTONE MUDSTONE LIMESTONE		
			PAMALUAN BEDS	BEBULU LS MEMBER	LIMESTONE MUDSTONE SANDSTONE	*Globigerinita stainforthi stainforthi*	600 TO 2733
					MUDSTONE COAL SANDSTONE LENSES	*Globigerinita dissimilis dissimilis* *Globigerina binaleneis*	466 TO 1616
	OLIGOCENE		TUJU BEDS		MUDSTONE	*Globorotalia kugleri*	0 TO 1233
			TELAKAI BEDS		CALCIRUDITE	*Globorotalia (T) centralis* *Globogenna gortanil gortanil*	1233 TO 2600
	LATE EOCENE				MUDSTONE	*Cribahantkenina inflata* *Globorotalia (T) cerroazunensis*	
			KUARO BEDS		CALCIRUDITE BROWNSHALE SANDSTONE CONGLOMERATE	*Globigerapsis mexicana*	600 TO 1750
PRE-TERTIARY			BASEMENT		METASEDIMENTARY SERPENTINE-EXTRUSIVE	NONE (IGNEOUS, METAMORPHIC)	

Geometry and material properties

The study performed the model of Kutai Basin which comprises two layers rock formation, Kampung Baru Formation and Balikpapan Formation. The model has Kampung Baru sandstone layer at the depth of 0 – 600 meters, and Balikpapan limestone at the depth of 600 – 1600 meters. The model is quite simplistic and assume that the interface of two layers is planar, neglecting anticline of the formation. The alluvium soil that should be on the top of the basin is also unconsidered. The sequence interbedded of mudstone and lignite in the Kampung Baru sandstone is also neglected due to their thickness is very thin compared to the sandstone layer thickness. Similarly, the interbedded lignite and sandstone in Balikpapan limestone is also neglected.

The size of the model is 3200 m × 3200 m × 1600 m (Figure 2). Sandstone is on upper layer of the model, from 0 to 600 m, while limestone at the lower layer, from 600 to1600 m. Due to the grid size is 160 m × 160 m × 80 m, the model generated 8,000 grids. The injection well of CO_2 was located at x = 1600 m, y = 1600 m, and z = 800 m. The distance between of the injection well and the lateral boundaries and vertical boundary is 1600 and 800 meters, respectively. These distances are sufficient to minimize boundary effect. In addition, the injection period was simulated for one year only so that the flow of CO_2 cannot affect the boundary of the model. For the need of geomechanical simulation, the bottom, left and right edge boundary was fixed, whereas the top boundary is freed. The properties of sandstone and limestone of the model are shown in Table 2. Mohr-Coulomb constitutive model was employed to analyze geomechanical behavior. Other properties of sandstone and limeston were gathered from extensive litterature study.

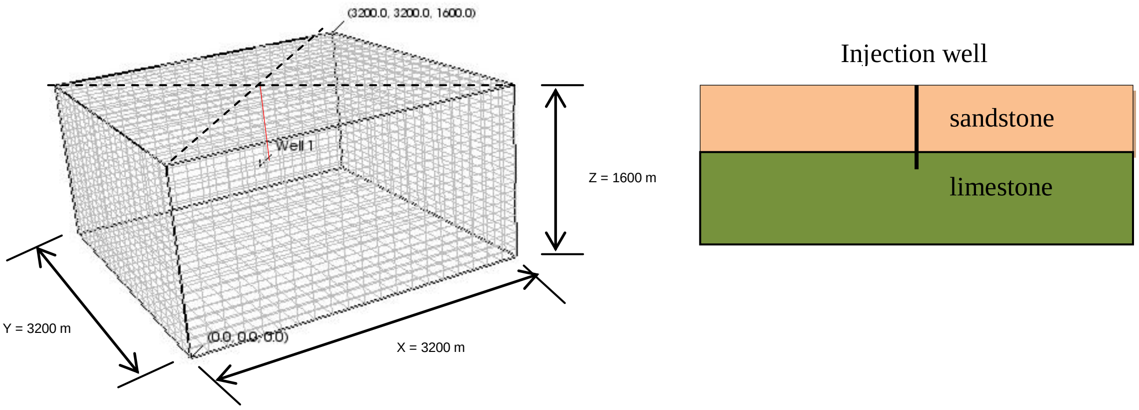

Figure 2. Schematic grid of the model.

Table 2. Material Properties

Property	Kampung Baru Sandstone	Balikpapan Limestone
Permeability (mD)	15	5
Porosity	0.3	0.15
Density (kg/m^3)	2000	2700
Bulk Modulus (GPa)	0.7	65
Shear Strength (Mpa)	8	10
Cohesive strenght (Mpa)	10	10
Tensile Strength (MPa)	4	5
Friction Angle (°)	30	30

Results and Discussions

Injection of CO_2 into the model was simulated over the period of 12 days, 3.5 months and one year with the injection rate of 35 kg/s or 3024 ton/day. Figures 3 presents the hydraulic pressure and the distribution of CO_2 plume during the injection in 12 days. It can be seen that the hydraulic pressure around the injection point has increased significantly, from natural hydraulic pressure of 9 MPa to 11 MPa. The increase of the hydraulic pressure due to the injection is relatively fast compared to that simulated for Ainoura Sandstone that we studied previously (Arsyad et al., 2012). The plume of CO_2 spreads about 80 meters beyond the injection point. The total CO_2 injected into the model is 36,288 tons.

Figure 4 shows the hydraulic pressure and the distribution of CO_2 plume at 3.5 months injection. The spread of CO_2 plume take a larger area compared to 12 days injection, as we can expect. The hydraulic pressure rises to 12.5 MPa, exceeding the natural hydraulic pressure 9 MPa. As the injection continues to one year period, the hydraulic pressure increases significantly, reaching 13 MPa (Figures 5 and 6).

The volume of the injected CO_2 is accounted for 312,570 tons for 3.5 months period and 1,1 million tons for one year period. The spreading of CO_2 is observed 120 meters from the injection point when the injection duration is 3.5 months (Figure 7). On the other hand, the CO_2 spreads up to 160 meters for one year period of injection (Figure 7). This suggested that the injection of CO_2 for one year period still reserve such clearance distance without CO_2, about 640 meters to the ground surface. By assuming that the migration rate of CO_2 is constant, it can be predicted that for 100 years period, the injection will drive CO_2 plume flowing up to 261 meters from the injection point, indicating the injection reserves the clearence without CO_2, 540 meters to the ground surface. The result suggested that the injection may not contaminate the groundwater table which is located several meters below the ground surface, even if the injection is conducted for 100 years period. It should be noted that the result of the simulation is on the basis of assumption that there is no fracture in the formation that would become a channel for CO_2 to reach groundwater quickly. The total volume of CO2 injected at 100 years period is 110,000 million tons. This reveals large storage capacity of the model for CO_2. Figures 8, 9 and 10 present geomechanical effect yielded by CO_2 injection. The injection of CO_2 over 12 days period was found to yield such vertical displacement, indicating a ground uplift. The uplift was accounted for 4 - 17.5 mm where the maximum uplift occurred at the centre of the model, around the injection point (Figure 8). The uplift continued as the injection of CO2 was simulated over 3.5 months period. It was found that the injection generates 7.5 – 23 mm uplift (Figure 9), while one year injection generates 15 – 45 mm ground uplift (Figure 10). The rate of uplift is quite high, contributing a significant geomorfological impact. It can be predicted that the injection would generate 304 mm uplift for 10 years period of injection (Figure 11). This may relate to the potential crack propagated by the injection as the hydraulic pressure far exceeding the strength stress of rock formation or the ultimate strain of the rock evolving to be failure crack.

Conclusions

1. Injection of CO_2 into Kutai Basin will drive the migration of CO_2 plume which in turn to increase hydraulic pressure in the basin.
2. The increase of hydraulic pressure can exceed the natural hydraulic pressure in the rock formation. Over one year period of injection, the hydraulic pressure can increase

to 13 MPa, or 4 MPa above the natural hydraulic pressure 9 MPa in case the injection point located at 800 meters depth. Total volume of CO_2 injected into the basin is estimated 1.1 million tons CO_2, indicating large storage capacity of the basin for CO_2 geological storage.

3. As the hdyraulic pressure increase significantly, the injection of CO_2 also can generate a considerable ground uplift. The ground uplift is accounted for 304 mm for one year period of injection.
4. The results suggested the potential storage of Kutai Basin for CO_2 is prospective whereas its geomechanical impact nessecitates a carefull examination prior to the injection of CO_2 in field scale is commenced.

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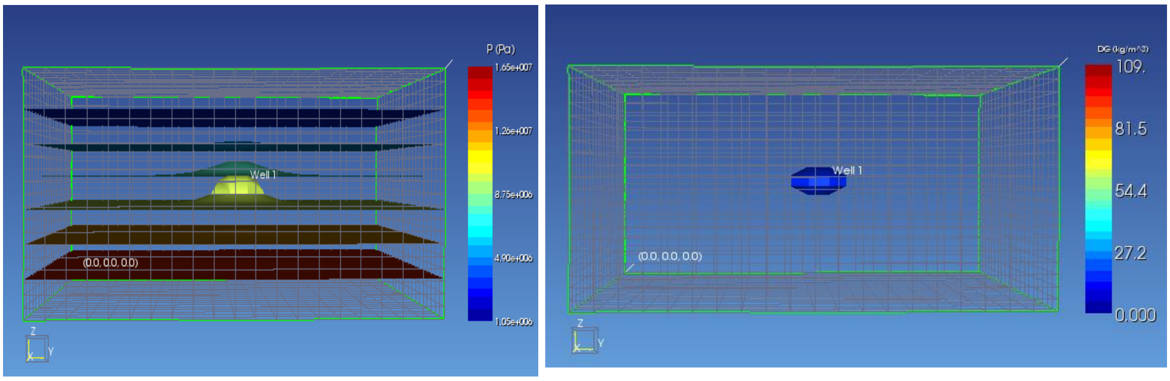

(a) (b)

Figure 3. Hydraulic pressure (a) and CO_2 plume (b) due to injection of CO_2 over the period of 12 days.

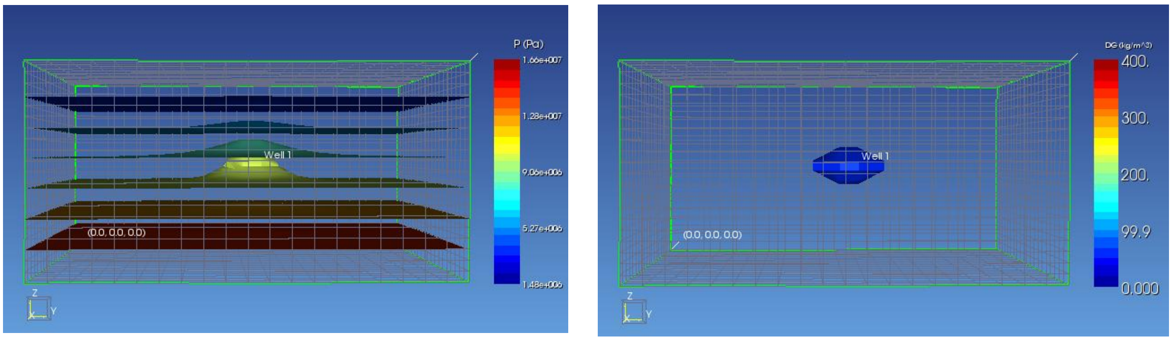

Figure 4. Hydraulic pressure (a) and CO_2 plume (b) due to injection of CO_2 over the period of 3.5 months.

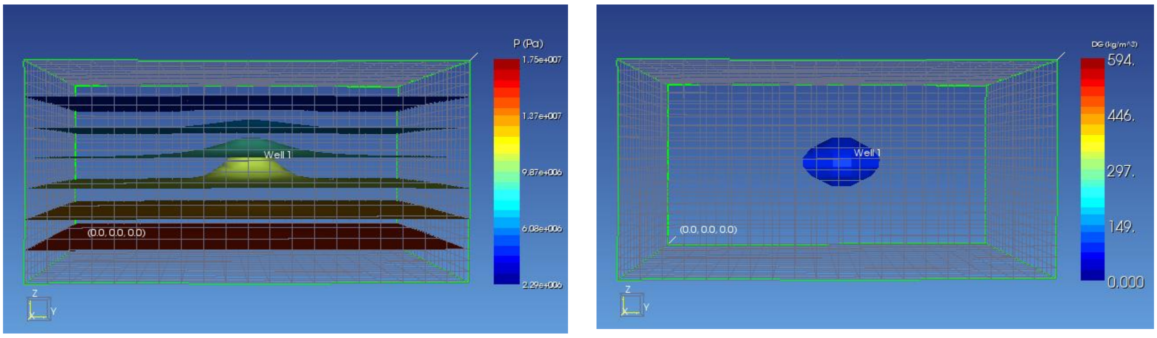

Figure 5. Hydraulic pressure (a) and CO_2 plume (b) due to injection of CO_2 over the period of one year.

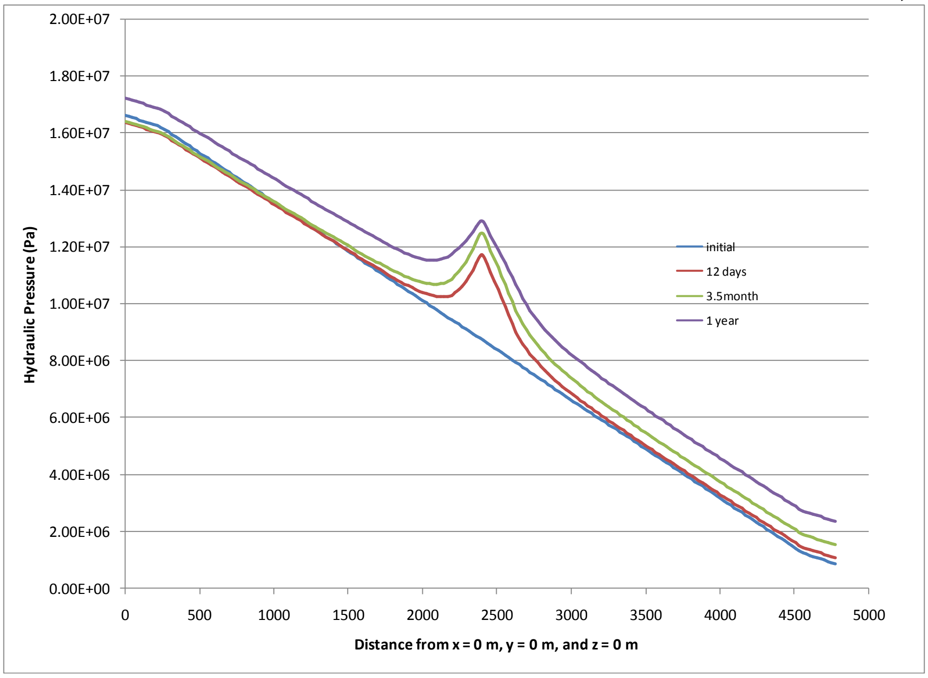

Figure 6. The increase of hydraulic pressure around the injection point.

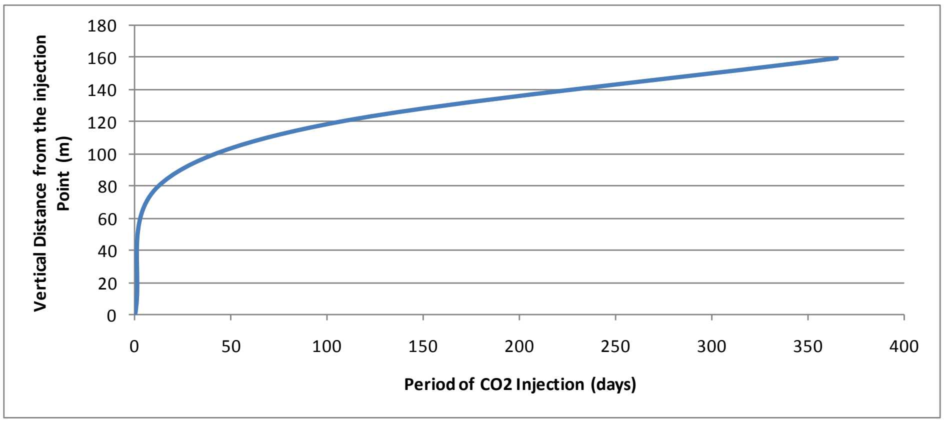

Figure 7. The spread of CO_2 plume .

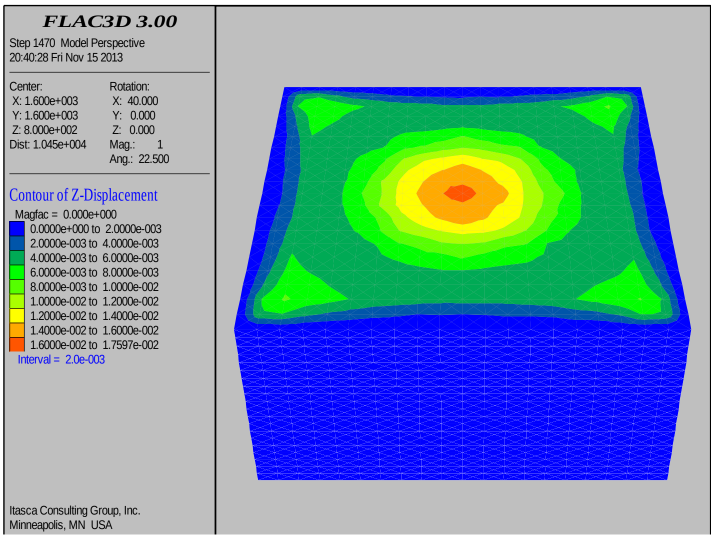

Figure 8. Ground uplift drivened by CO_2 injection over 12 days.

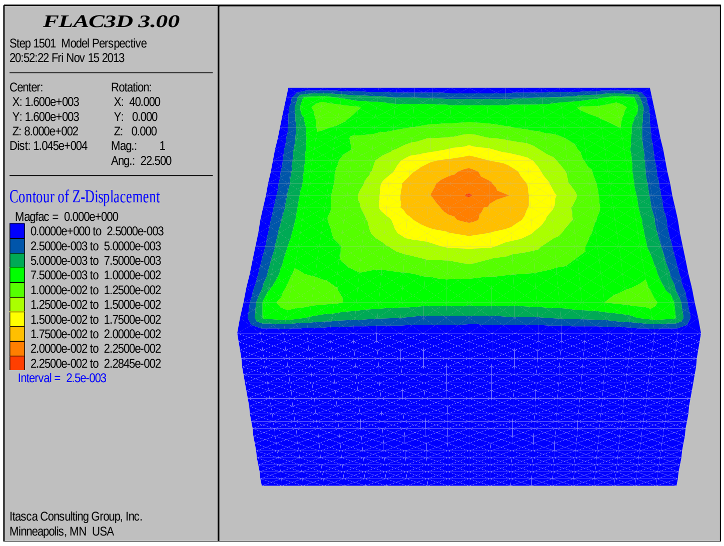

Figure 9. Ground uplift drivened by CO_2 injection over 3.5 months.

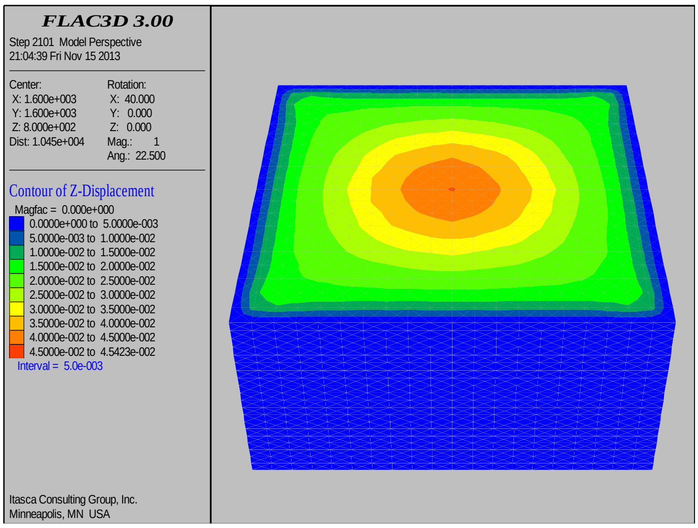

Figure 10. Ground uplift drivened by CO_2 injection over one year.

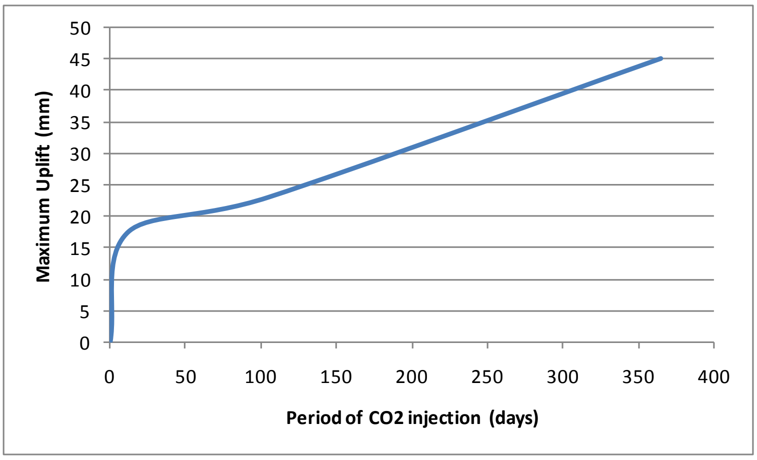

Figure 11. Maximum ground uplift drivened by CO_2 injection.